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CENG 5503 - Steel and Timber Structures

Chapter 3 : Compression Members

Objectives

- Introduction
- Typical cross-sections of compression members
- Classification of cross-section
  - Components of cross-section
  - Element Classification
- Design of Compression Members

Introduction

- A structural member is considered to be a compression member if it is designed primarily to resist axial compression, though some bending may also be present and accounted for in the design.
- If the bending action is quite significant, the member is termed as a beam-column and designed in a different way.
- Terms such as column, stanchions and struts are widely used to define a compression member.

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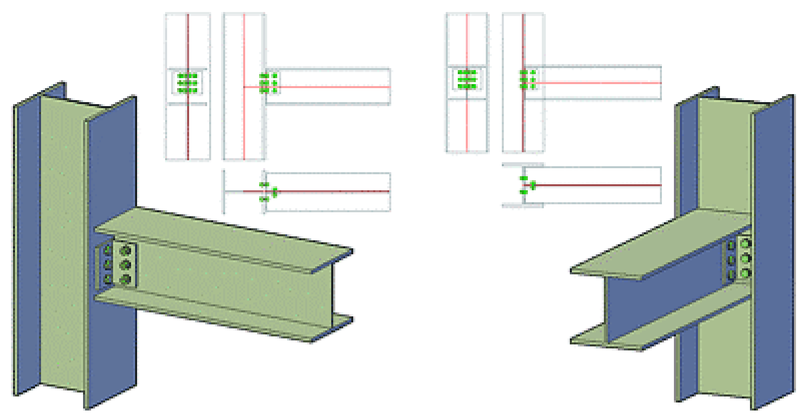
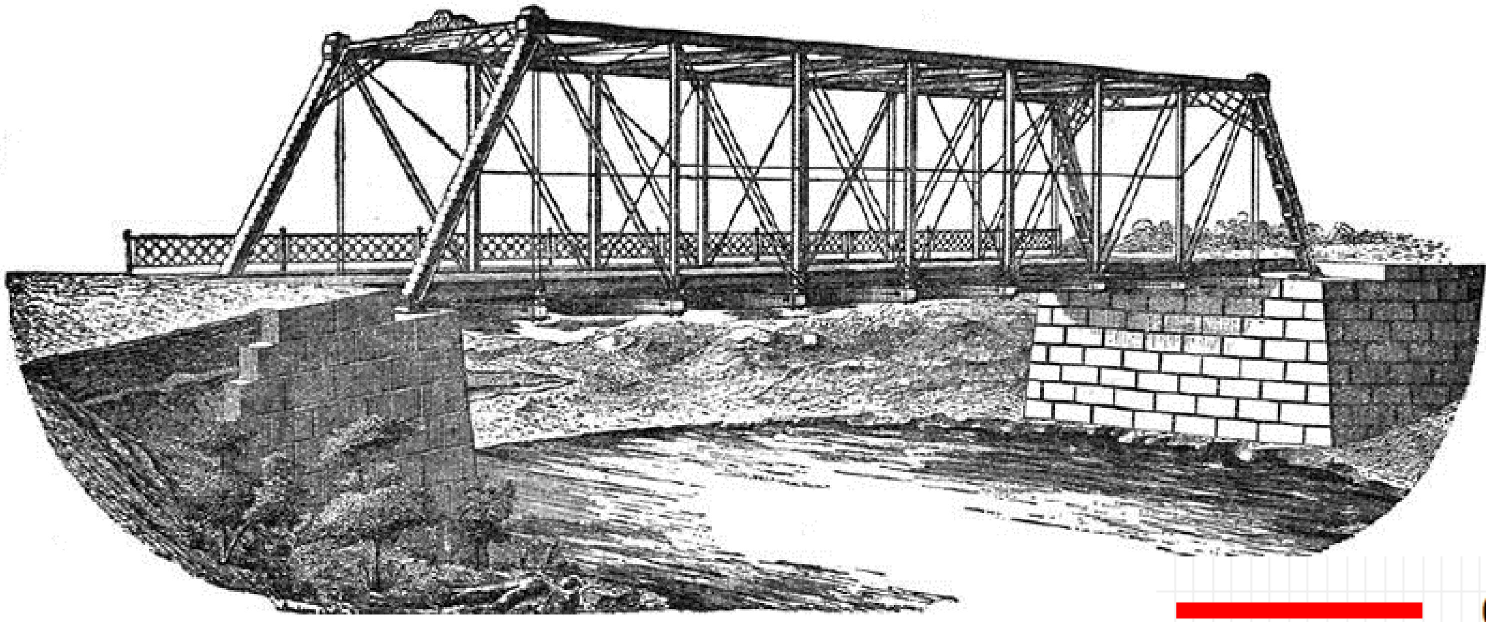
- Columns are ordinarily used in buildings, are vertical and transmit some actual load or beam reaction to another column or foundation.
- Stanchions are steel columns made of rolled steel sections (usually built – up) and carry heavy loads.
- Struts on the other hand are not necessarily vertical and are used as compression members in roof trusses and bridge trusses

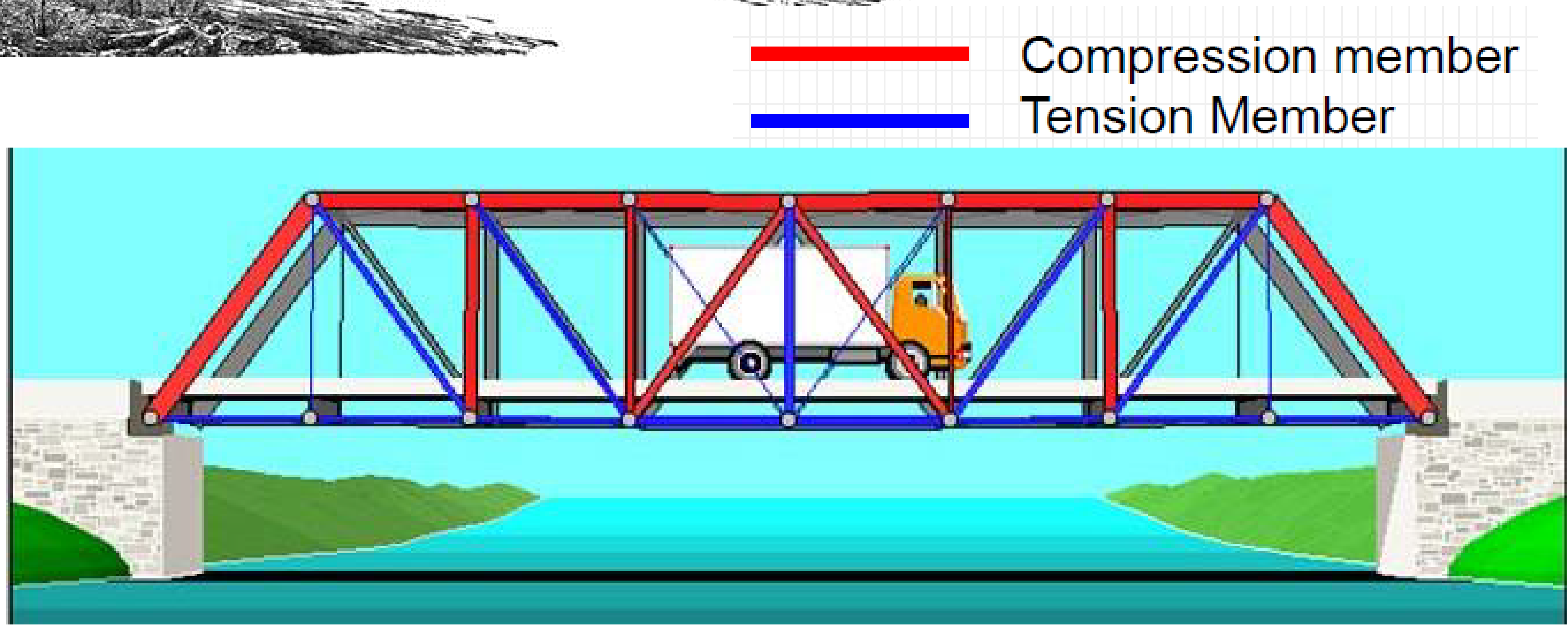
Compression members in buildings



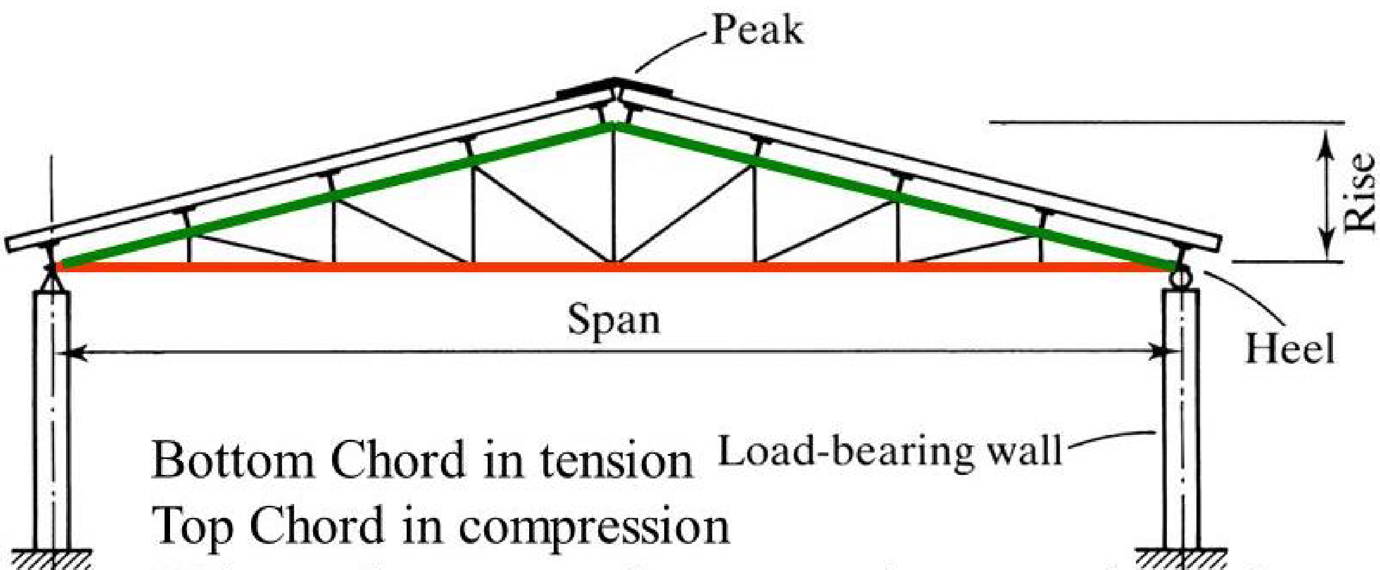
Compression member in supporting structures

Compression member in Bridges





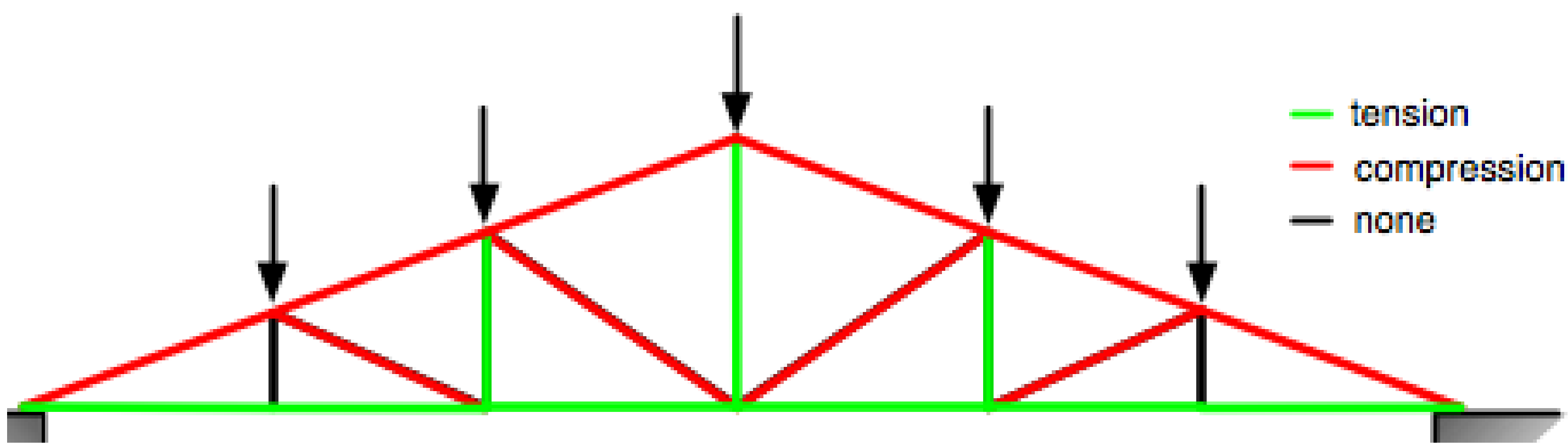
Compression member in Trusses



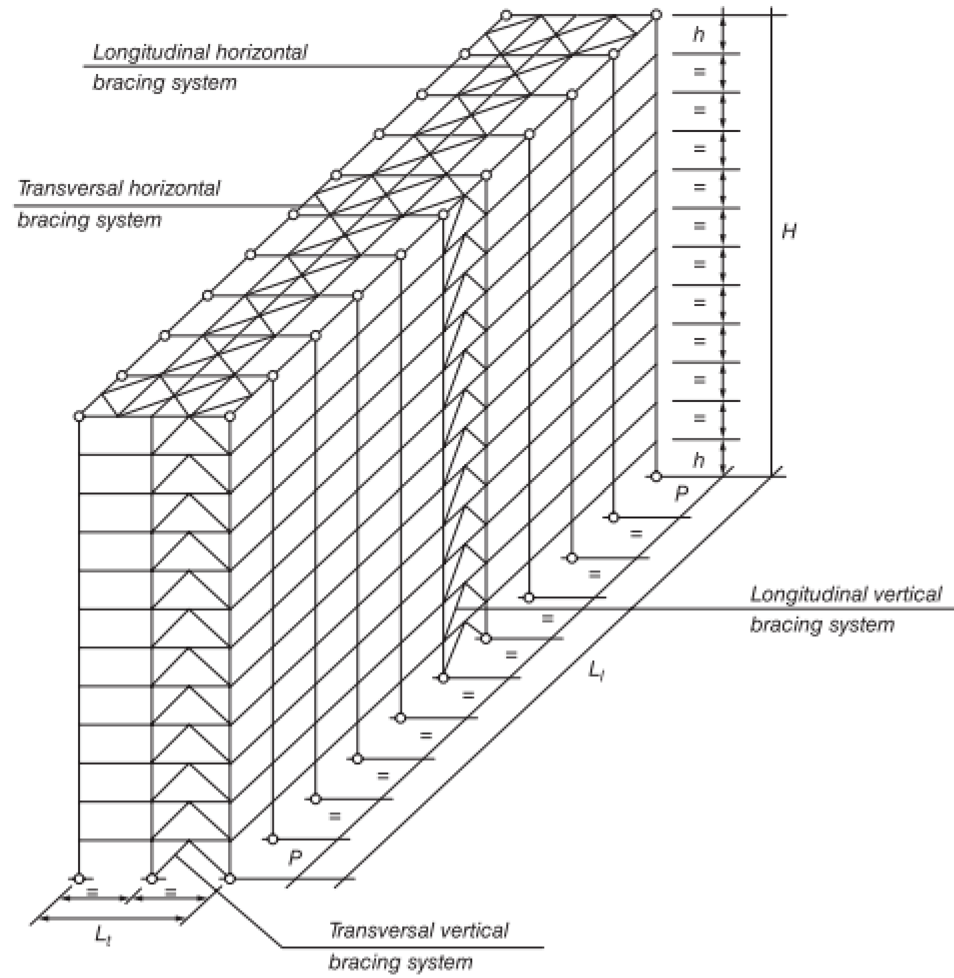
Bottom Chord in tension

Top Chord in compression

Web members: some in compression some in tension



Compression members in frame bracings



Depending on the direction of the load being applied either of the members may be a compression member where as the other acts as tension member.

The two main differences between tension and compression members are:

i. Tension members are held straight by means of tensile loads, while in the case of compression members, the compressive loads tend to bend the member out of the plane of loading.

ii. For bolted or riveted connections, the net area will govern the strength of a tension member, while for compression members the rivets & bolts are assumed to fill the holes.

Typical cross-sections

- Section should be proportioned such that to have the largest radius of gyration. i.e. less slender
- Rods, bars and plates are too slender to be used as compression members
- A circular pipe has the highest for the given cross-sectional area and is equal in all direction but very difficult to connect to other structural members.
- Rolled, compound and built-up section are used for columns.

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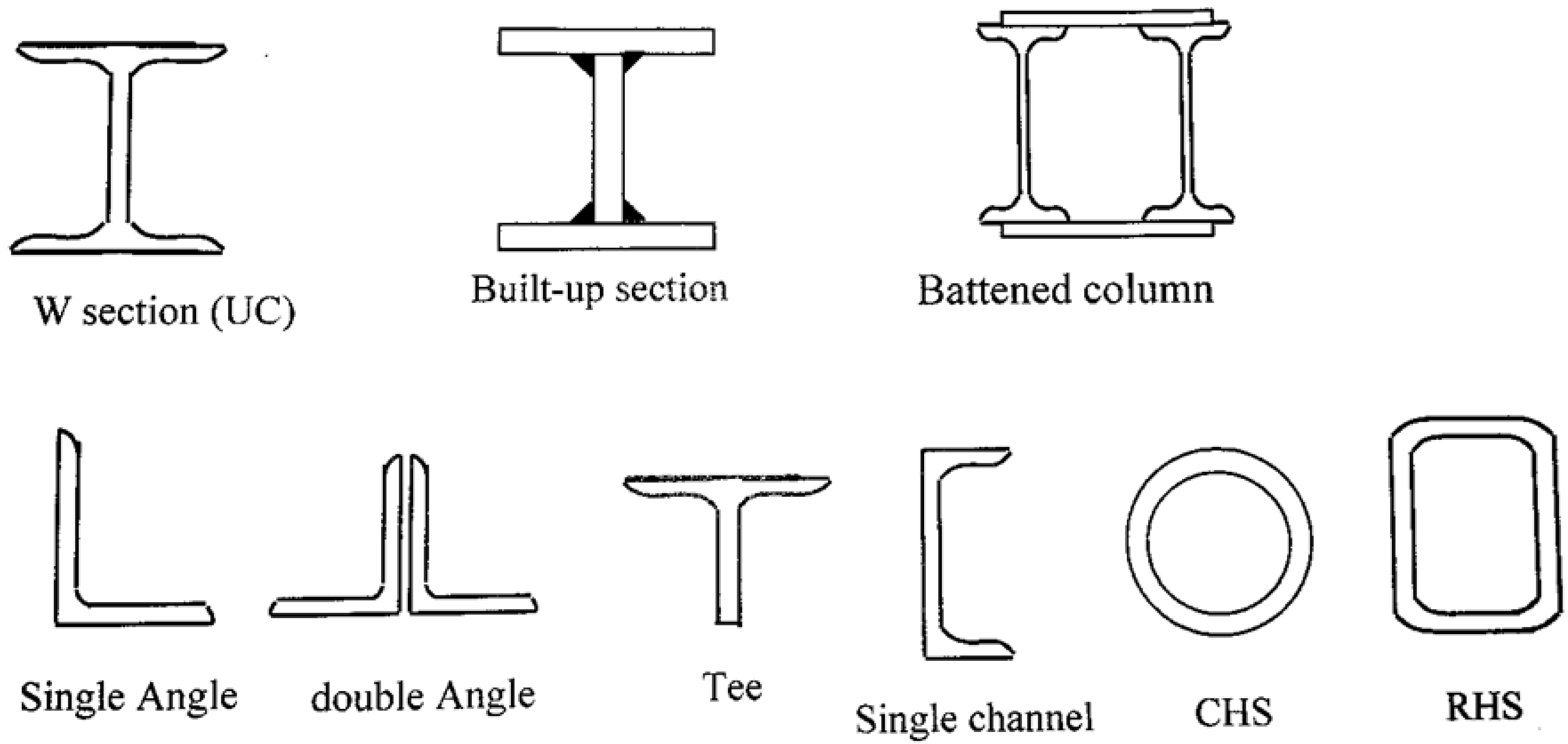
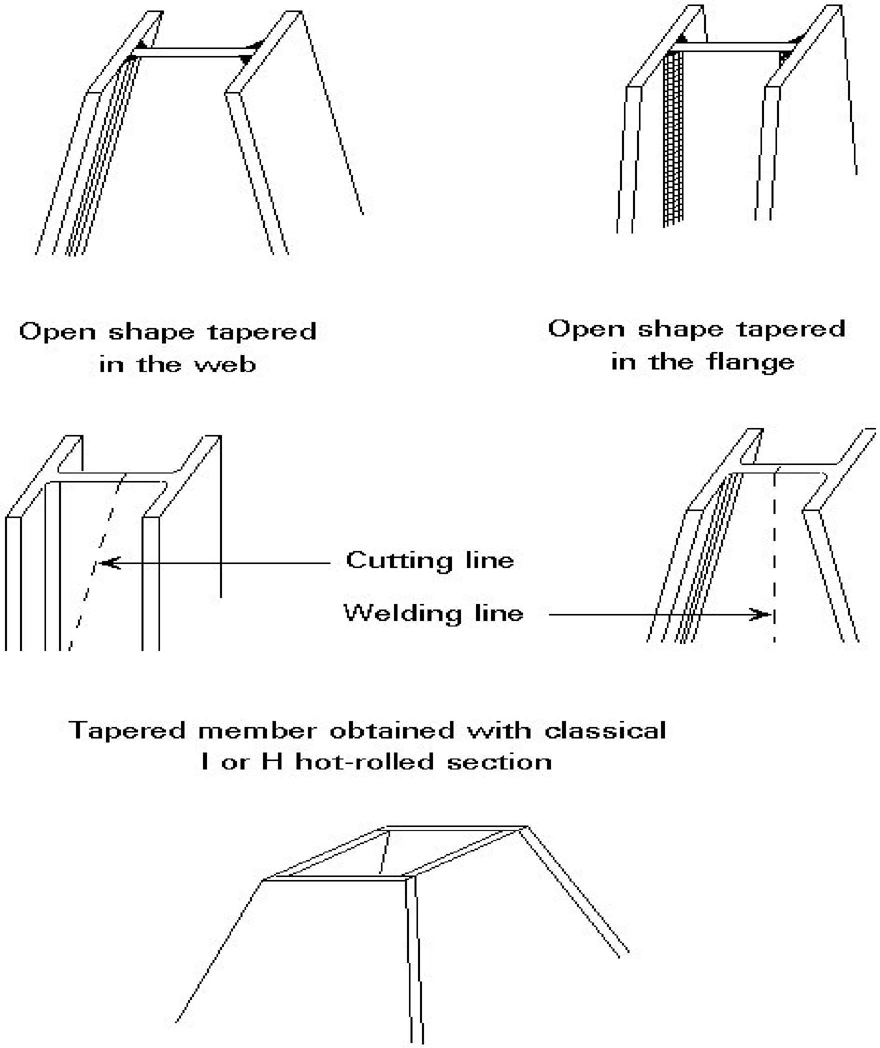


Figure. Compression member section



Welded box tapered in the two directions

Figure. Tapered members

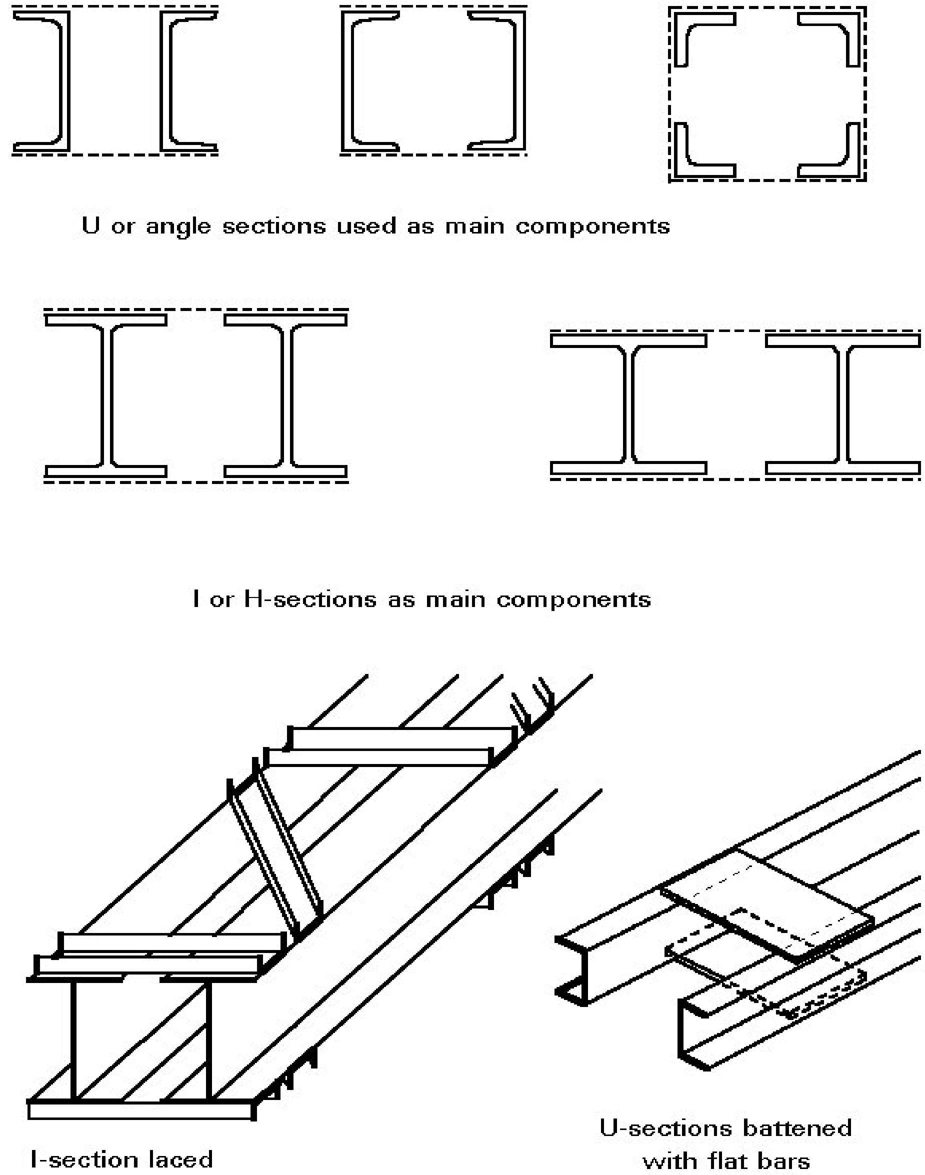
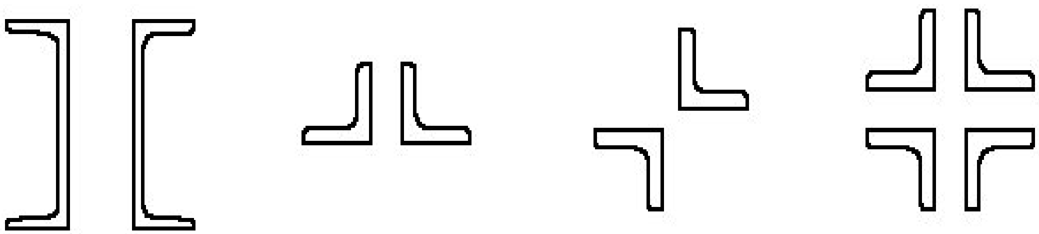
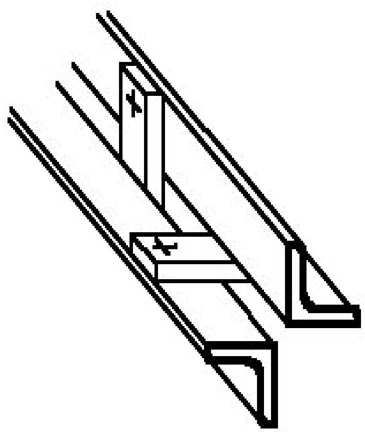


Figure. Built-up members



Closely spaced built-up members



Detail of star-battened member

Figure. Built-up members

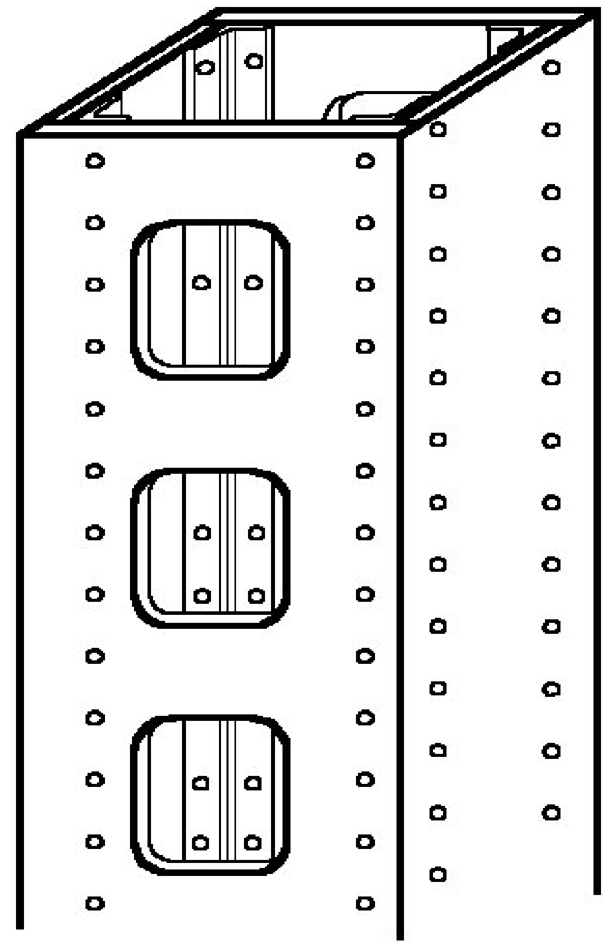


Figure. Perforated plate columns

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- Compression members can fail by yielding, inelastic buckling, or elastic buckling depending on the slenderness ratio of the members as well as in local buckling that is usually influenced by the relative thickness of the component elements that constitute the cross section.
- Members with low slenderness ratios generally tend to fail by yielding, whereas members with high slenderness ratios tend to fail by elastic buckling.
- Most compression members used in construction have intermediate slenderness ratios, and so the predominant mode of failure is inelastic buckling.

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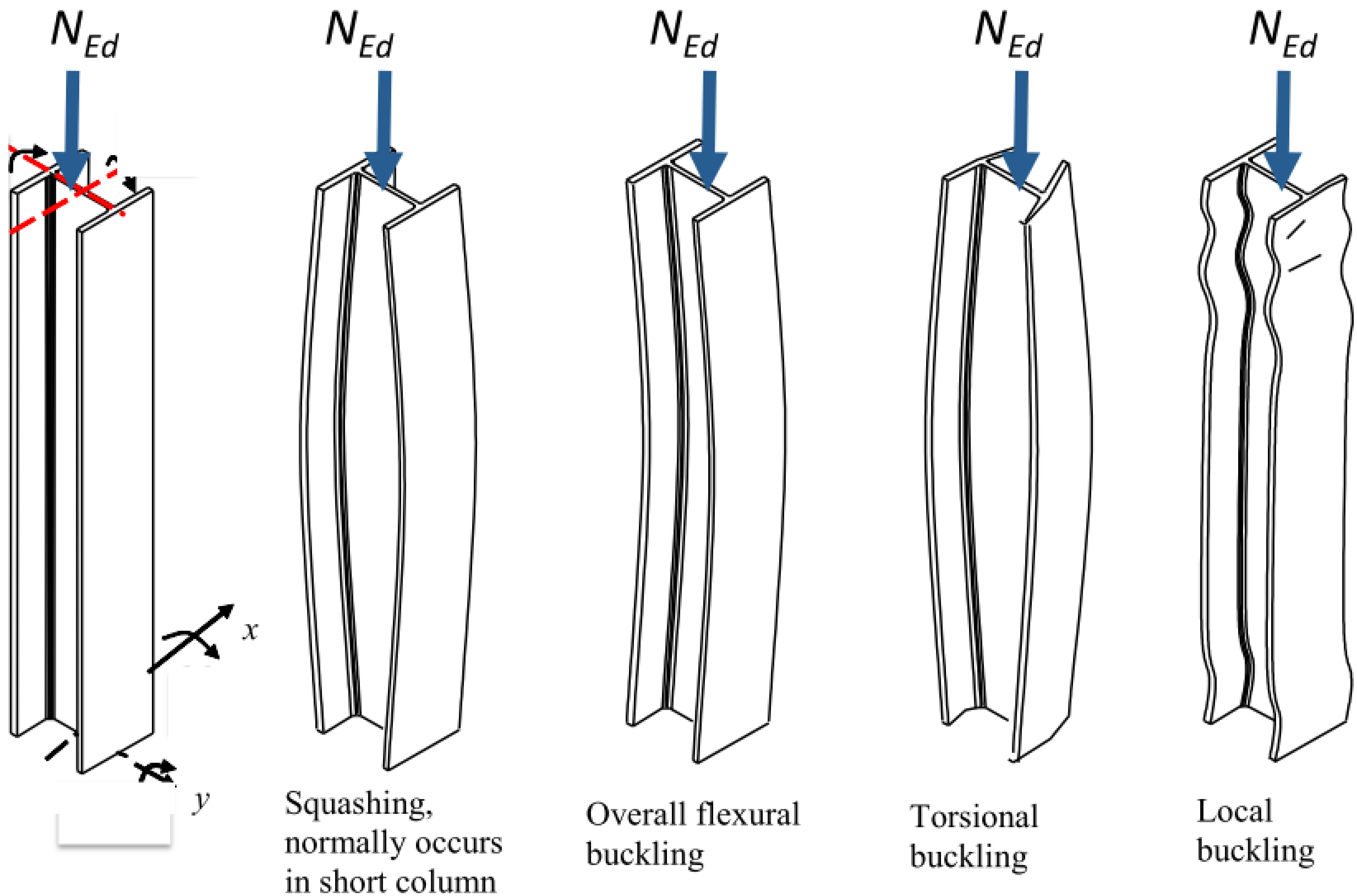
The resistance of a steel member subject to axial compression depends on ;

i. The cross section resistance or
ii. The occurrence of instability phenomena, phenomena, such as flexural buckling , torsional buckling or flexural -torsional buckling .

The resistance of a compression member decreases as its length increases, in contrast to the axially loaded tension member whose resistance is independent of its length.

Failure Types



Classification of Cross-section

- EBCS 3 1995 classifies sections into four categories,
- Class 1 cross sections, also known as *plastic sections* can develop their plastic moment resistance with the rotation capacity required for plastic analysis. Only cross sections falling in this class may only be used for plastic design.
- Class 2 cross sections can develop their plastic moment resistance but with limited rotation capacity. Cross-sections falling in this group are also known as *compact sections*.

cont'd

- Class 3 cross sections are those which can reach their "yield" moment but local buckling prevents the development of the plastic moment resistance.
  - In Class 3 sections, the stress in the extreme fibres should be limited to the yield stress because local buckling prevents development of the plastic moment capacity.
  - Cross-sections falling in this group are also known as *semi-compact sections*.

cont'd

- Class 4 cross sections, also known as *thin-walled cross-sections*, are those in which local buckling is liable to prevent the development of the "yield" moment; i.e., premature buckling occurs before yield is reached.
- EBCS 3 1995, the classification of sections depends on the classification of flange and web elements. The classification also depends on whether the compression elements are in pure compression, pure bending or combined axial force and bending. Next slides discuss about these classification.

Components of cross-section

- Classification of a specific cross-section depends on the width-to-thickness ratio, b/t, of each of its compression elements.
- Compression element include any component plate which is either totally or partially in compression due to axial force or bending moment. i.e. *classification depends on the loading the section is experiencing*.

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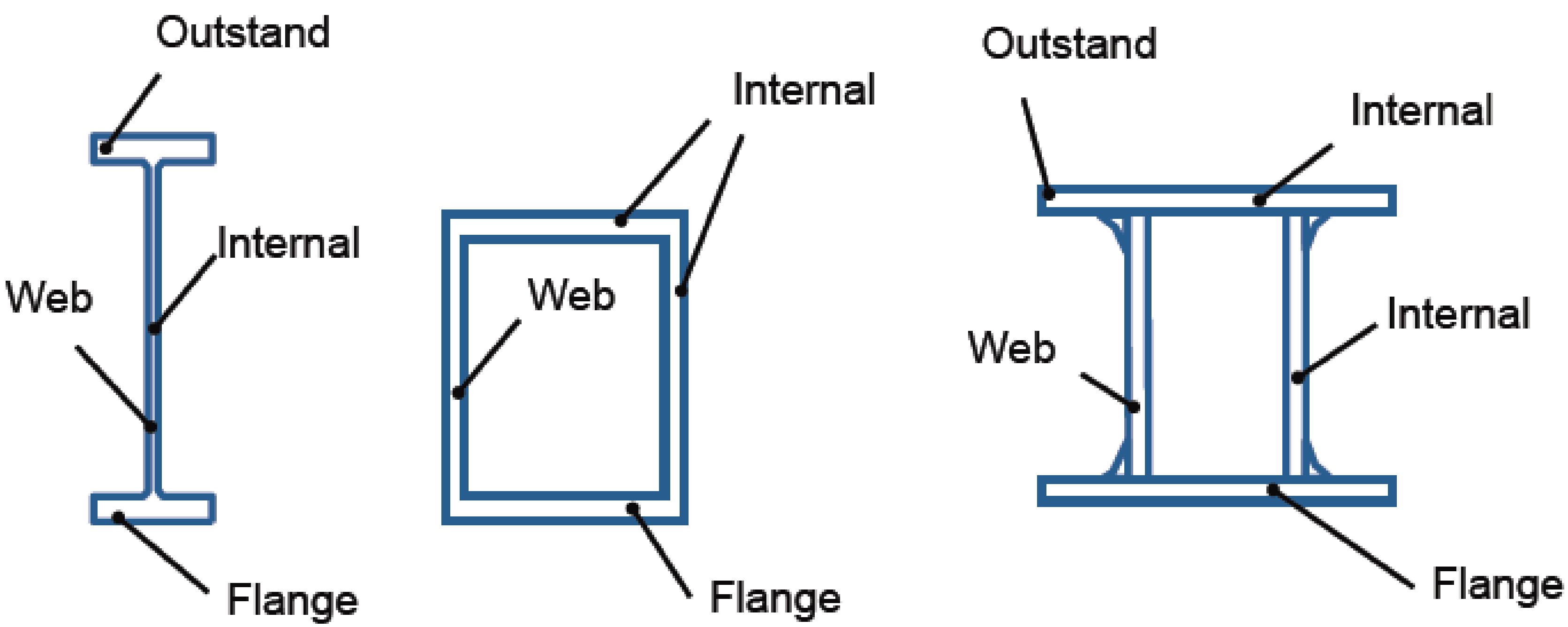
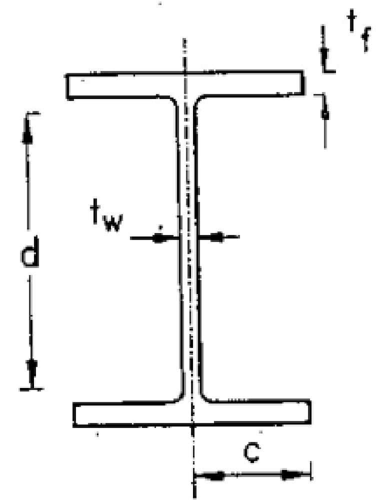
- A cross-section is composed of different plate elements, such as web and flanges, most of these elements, if in compression, can be separated into two categories,
  - Internal elements – these elements are considered to be simply supported along two edge parallel to the direction of compressive stress.
  - Outstand elements – these elements are considered to be attached along one edge and free on the other edge parallel to the direction of compressive stress.



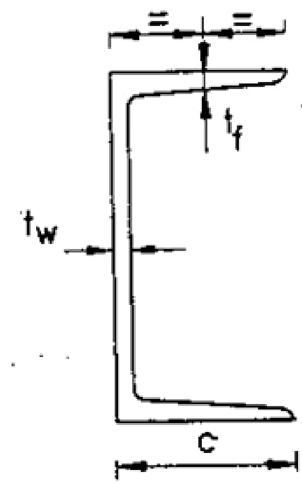
Rolled I-section Hollow section Welded box section

Element Classification

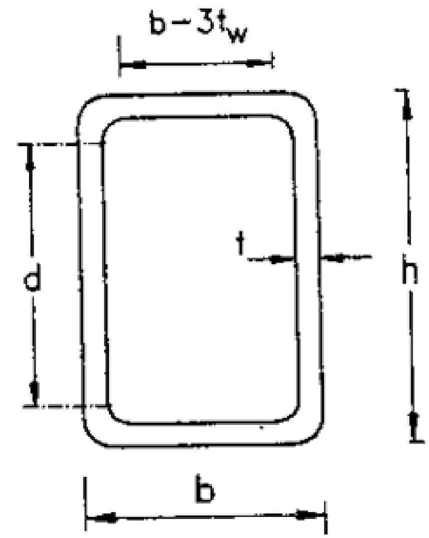
- Elements may be classified as plastic, compact or semi- compact if they meet the limits given in the following.
- If the section dimensions (see next slides) satisfy the limits shown in the tables, the section is classified as Class 1, Class 2, or Class 3 as applicable.
- A cross-section is classified by reporting the highest (least favorable) class of its constituent compression elements that are partially or wholly in compression.
- If a section fails to satisfy the limits for class 3 sections, it is classified as Class 4.



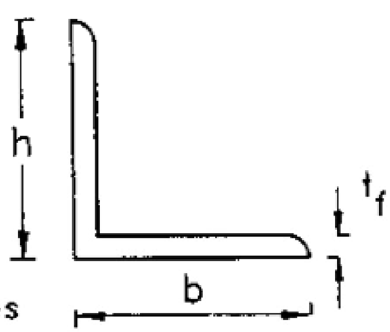
Rolled beams and columns



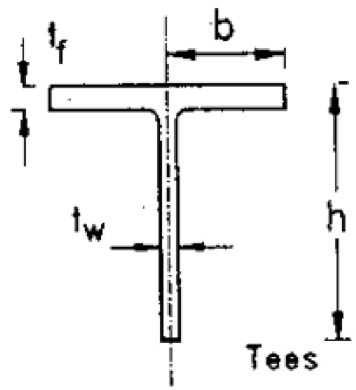
Rolled channels



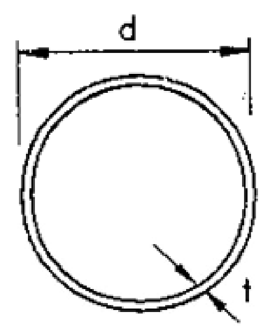
RHS



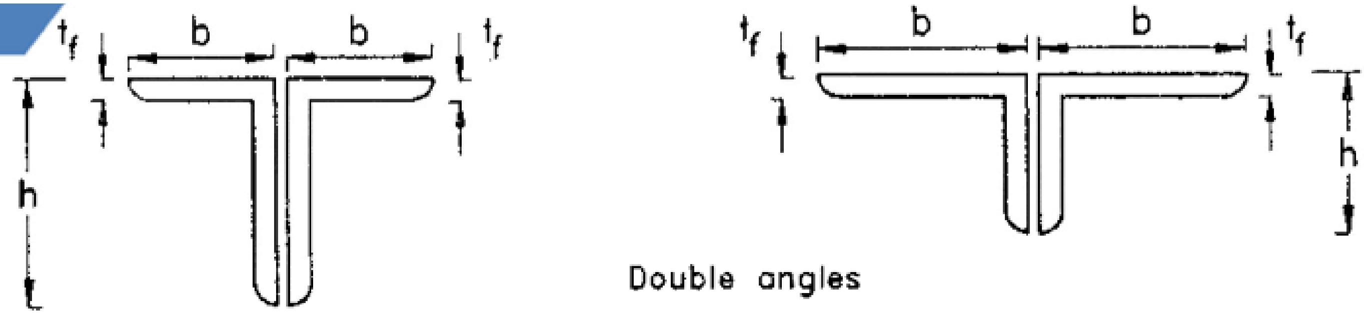
Angles



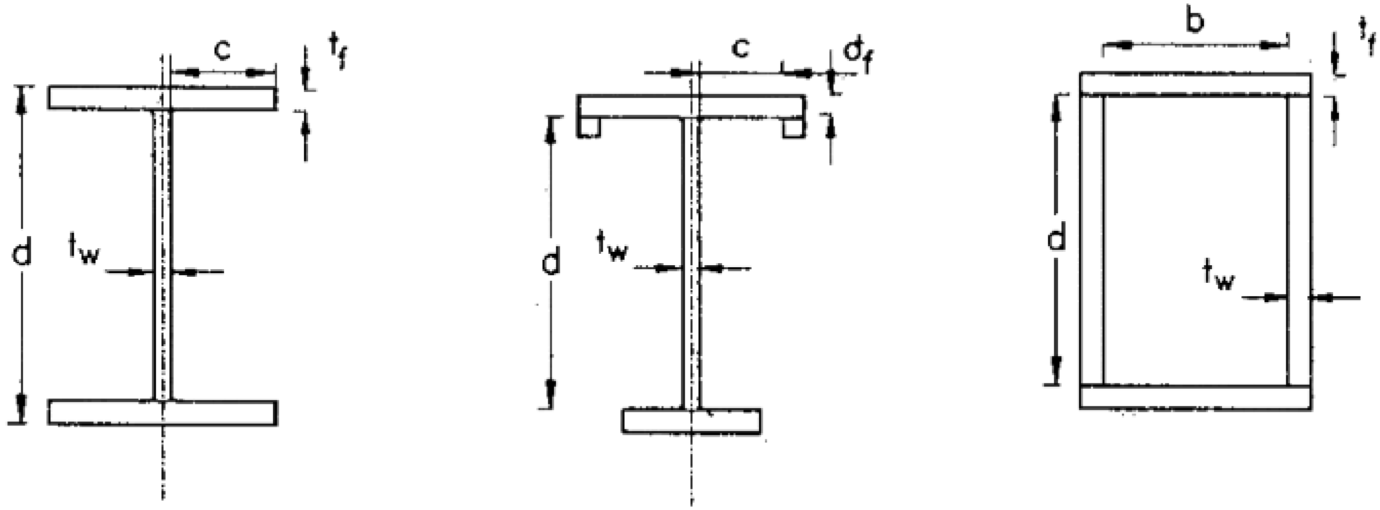
Tees



CHS



Double angles



Fabricated sections

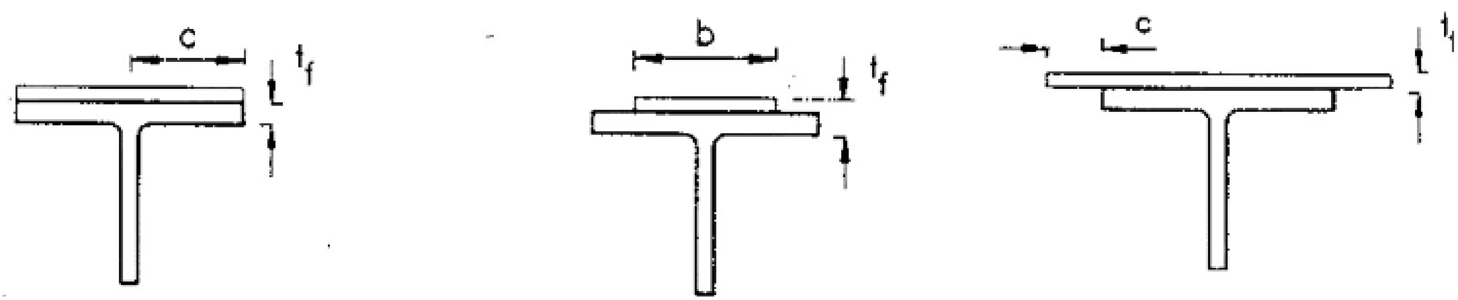


Table 3.1. Classification of Compression Sections According to EBCS 3 1995 (Modified to meet latest Euro code Standard).

Limiting Width-Thickness Ratios for Compression Elements (those exceeding these limits are taken as Class 4 section)					
Section	Element	Ratio Checked	Class 1	Class 2	Class 3
General	-	None	Assumed Class 3		
Rectangular	-	None	Assumed Class 2		
I - shape	Web	d/t_w (rolled) d/t_w (welded)	33ε	44ε	51ε
	Flange	c/t_f (rolled)	10ε	11ε	15ε
		c/t_f (welded)	9ε	10ε	15ε
Box	Web	d/t_w	33ε	38ε	42ε
	Flange	$(b-3t_f)/t_f$ (rolled)	42ε	42ε	42ε
		b/t_f (welded)	42ε	42ε	42ε
Channel	Web	d/t_w	33ε	38ε	42ε
	Flange	b/t_f	10ε	11ε	15ε
T-Shape	Web	h/t_w	33ε	38ε	42ε
	Flange	$b/2t_f$ (rolled)	10ε	11ε	15ε
		$b/2t_f$ (welded)	9ε	10ε	14ε
Angle	-	h/t $(b+h)/(2t)$	NA	NA	15.0ε 11.5ε
Round Bar	-	None	Assumed Class 1		
Pipe	-	d/t	$50\varepsilon^2$	$70\varepsilon^2$	$90\varepsilon^2$
Double Angle	-	h/t	NA	NA	15.0
		$(b+h)/(2t)$			11.5ε

NA = Not Applicable

Cont'd

- One of the major factors in determining the limiting width-thickness ratio is the parameter ε.
- This parameter is used to reflect the influence of yield stress on the section classification.

$$\varepsilon = \left(235/f_y \right)^{1/2}$$

Parameter	Steel Grade		
	Fe 360	Fe 430	Fe 510
f_y	235	275	355
ε	1	0.92	0.81

Cont'd

Therefore columns are distinguished as

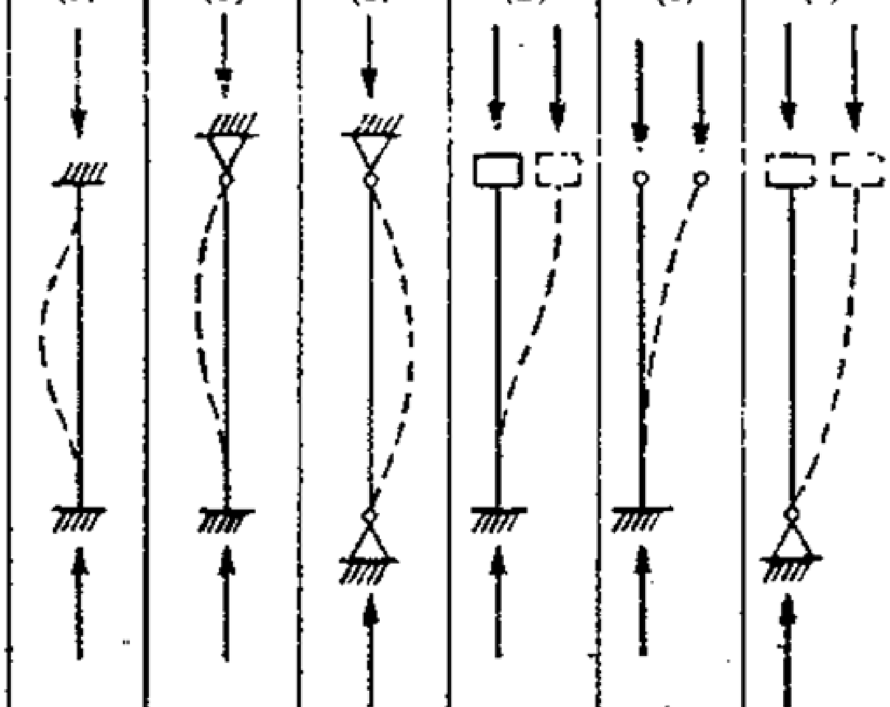
- ➢ Stocky Columns with characteristics of
  - Very low slenderness, unaffected by overall buckling and failure results from rupture of cross-section
- ➢ Slender Columns
  - Large slenderness with characteristics of
    - Unaffected by imperfection, ultimate failure load ≈ Euler Load and independent of yield stress.
  - Medium slenderness with characteristics of
    - Affected by imperfection and failure load is less than Euler Load

Effective Length

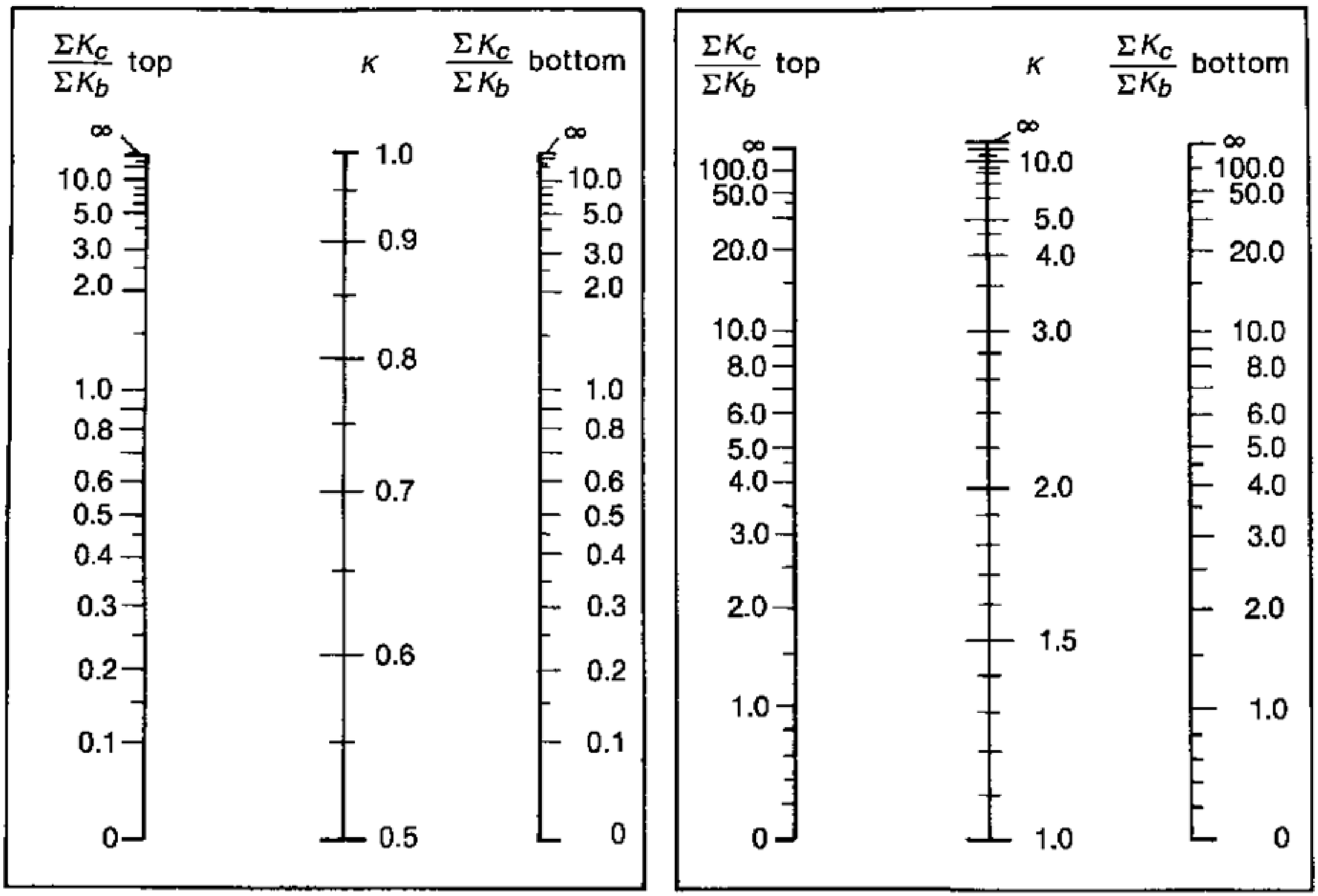
- The effective length factor k is a factor which, when multiplied by the actual un-braced length L of an end-restrained compression member, will yield an equivalent pinned-ended member whose buckling strength is the same as that of the original end-restrained member.
- For a prismatic member, the effective length factor can be determined from different method which are given in the next slides.

Method I

- The following general recommendat ion can be used if support condition can be represented in the figure.

	(a)	(b)	(c)	(d)	(e)	(f)
Buckled shape of column shown by dashed line						
Theoretical K value	0.5	0.7	1.0	1.0	2.0	2.0
Recommended design values when ideal conditions are approximated	0.65	0.80	1.0	1.2	2.10	2.0
End conditions code	 Rotation fixed, Translation fixed Rotation free, Translation fixed Rotation fixed, Translation free Rotation free, Translation free					

Method II Using the aid of Nomographs



(a) Nonsway frames.

(b) Sway frames.

Method III - According to EBCS 3-1995 (for columns in multi story buildings)

1. For the theoretical models shown in next slide the distribution factors η_1 and η_1 is given by,

$$\eta_1 = \frac{K_c}{K_c + K_{11} + K_{12}}$$

$$\eta_2 = \frac{K_c}{K_c + K_{21} + K_{22}}$$

Where: K_c is the column stiffness I/L

K_{ij} is the effective beam stiffness coefficient

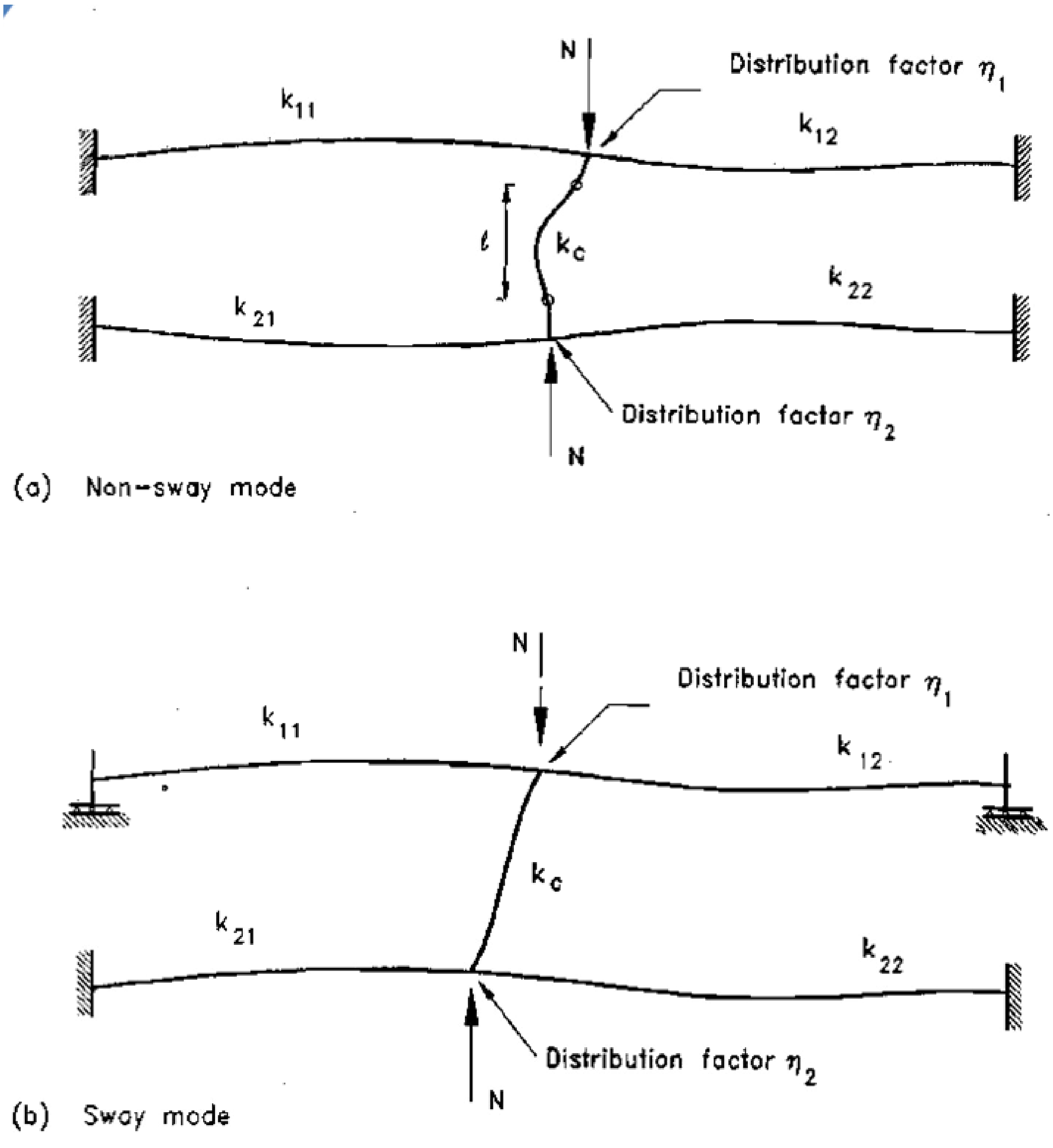


Figure : Distribution factor for columns

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2. For continuous columns shown in next slide the distribution factors η_1 and η_1 is given by,

$$\eta_1 = \frac{K_c + K_1}{K_c + K_1 + K_{11} + K_{12}}$$

$$\eta_2 = \frac{K_c + K_2}{K_c + K_2 + K_{21} + K_{22}}$$

Where: K_1 and K_2 is the column stiffness for the adjacent column

Figure : Distribution factor for continuous columns

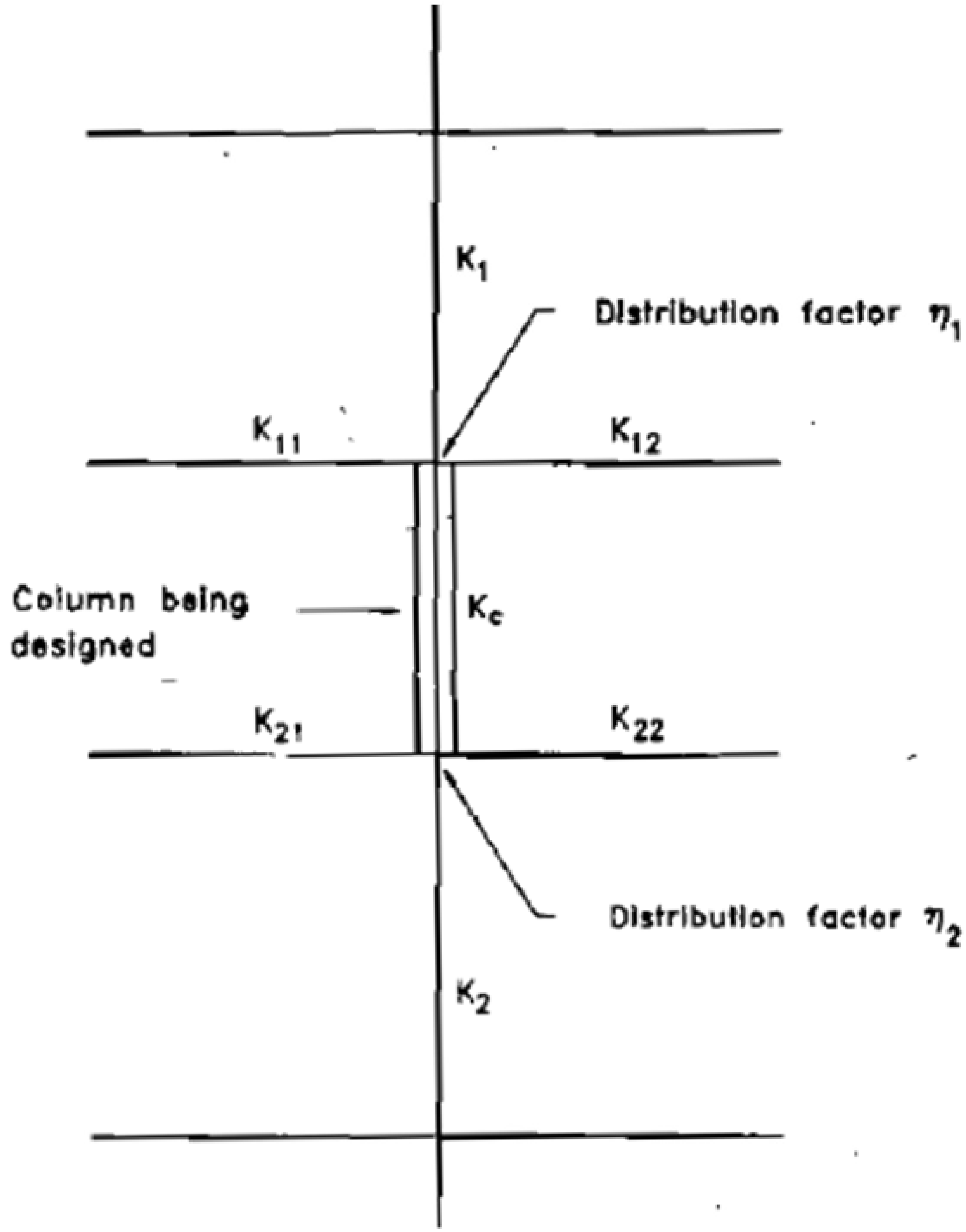


Table 4.7 Approximate Formulae for Reduced Beam Stiffness Coefficients due to Axial Compression

Conditions of rotational restraint at for end of beam	Effective beam stiffness coefficient K (provided that beam remains elastic)
Fixed	$1.0\ I/L\ (1 - 0.4\ N/N_E)$
Pinned	$0.75\ I/L\ (1 - 1.0\ N/N_E)$
Rotation as at near end (double curvature)	$1.5\ I/L\ (1 - 0.2\ N/N_E)$
Rotation equal and opposite to that at near end (single curvature)	$0.5\ I/L\ (1 - 1.0\ N/N_E)$

NOTE: In this Table $N_E = \pi^2 EI/L^2$

(10) The following empirical expressions may be used as conservative approximations:

(a) Non-sway mode

$$I/L = 0.5 + 0.14\,(\eta_1 + \eta_2) + 0.055\,(\eta_1 + \eta_2)^2$$

or alternatively:

$$I/L = \left[\frac{1 + 0.145\,(\eta_1 + \eta_2) - 0.265\,\eta_1 \times \eta_2}{2 - 0.364\,(\eta_1 + \eta_2) - 0.247\,\eta_1 \times \eta_2}\right]$$

(b) Sway mode

$$I/L = \left[\frac{1 - 0.2\,(\eta_1 + \eta_2) - 0.12\,\eta_1 \times \eta_2}{1 - 0.8\,(\eta_1 + \eta_2) + 0.6\,\eta_1 \times \eta_2}\right]^{0.5}$$

Table: Effective stiffness coefficient for beams not subjected to axial load

4.5.3 Slenderness

(1) The slenderness λ shall be taken as follows:

$$\lambda = l/i \tag{4.32}$$

where i is the radius of gyration about the relevant axis, determined using the properties of the gross cross-section.

(2) The value of λ shall not exceed the following:

(a)	For members resisting loads other than wind loads	180
(b)	For members resisting self weight and wind loads only	250
(c)	For any member normally acting as a tie but subject to reversal of stress resulting from the action of wind	350

Design Criteria for Compression Members

- A number of design checks are required for compression members.
- In all cases, it is recommended that the forces and moments in the members are derived from an elastic global analysis.
- In addition to cross-sectional resistance, consideration should be given to overall buckling of members.
- Members in compression are susceptible to a number of buckling modes including local buckling (Class 4 or thin sections only), flexural buckling torsional buckling and flexural-torsional buckling.

Cont'd

- Compression members are to be designed in such a way that both the cross-sections resistance to applied loads be established and member capacity verified against possible buckling failures.
- This chapter will cover only buckling resistance of Axially loaded compression members.
- These will be presented for EBCS 3 1995 Specification as follow.

Cont'd

Compression members shall be checked for:

1. Resistance of cross-sections
2. Resistance to buckling

a) Compression Resistance of Cross-section

- For members in axial compression, the design value of the compressive force $N_{c,Sd}$ at each cross-section shall satisfy

$$N_{c,Sd} \leq N_{c,Rd}$$

where: Where Nc.Rd = design compression resistance of the cross-section, taken as a smaller of either the design plastic resistance Npl,Rd of the gross section or the design local buckling resistance No,Rd of the gross section where, again, Npl,Rd and No,Rd are determined as in the following expressions:

a) the design plastic resistance of the gross section

$$N_{pl.Rd} = Af_y/\gamma_{M0}$$

b) the design local buckling resistance of the gross section

$$N_{o.Rd} = A_{eff}f_y/\gamma_{M1}$$

where A_{eff} is the effective area of the cross-section,

The design compression resistance of the cross-section $N_{c.Rd}$ may be determined as follows:

Class 1, 2 or 3 cross-sections: $N_{c.Rd} = Af_y/\gamma_{M0}$

Class 4 cross-sections: $N_{c.Rd} = A_{eff}f_y/\gamma_{M1}$

The partial safety factors are γ_{MO} = 1.1 and γ_{M1} = 1.1.

Resistance of Compression Members against buckling

Flexural Buckling Resistance of Compression members

Axially loaded compression members designed to resist a factored axial force of Nc.sd, calculated using appropriate load combinations must satisfy the condition:

$$N_{c.Sd} \leq N_{b,Rd}$$

The design buckling resistance of compression member shall be taken as

$$N_{b,Rd} = \chi \beta_A \frac{A f_y}{\gamma_{M1}}$$

Where:

β_A = 1 for Class 1, 2 and 3 cross-sections

$\beta_A = A_{eff}/A$ for Class 4 cross-sections

Aeff = is the effective cross-section for Class 4 cross-sections

A = gross area

χ = is the reduction factor for the relevant buckling mode

Cont'd

- The value χ for the appropriate non-dimensional slenderness $\bar{\lambda}$, is given by

$$\chi = \frac{1}{\phi + \left(\phi^2 - \bar{\lambda}^2\right)^{0.5}} \qquad but\ \chi \leq 1\ for\ 0.2 \leq \bar{\lambda} \leq 3.0$$

$$\chi = 1.0 \quad \text{for } \chi \leq 0.2 \qquad \phi = 0.5\left[1 + \alpha\left(\bar{\lambda} - 0.2\right) + \bar{\lambda}^2\right]$$

$$\bar{\lambda} = \sqrt{\frac{Af_y}{N_{cr}}} \text{ for Class 1,2 and 3 cross-sections}$$

$$\bar{\lambda} = \sqrt{\frac{A_{eff} f_y}{N_{cr}}} \text{ for class 4 cross-sections}$$

For slenderness $\bar{\lambda} \leq 0.2$ or for $\frac{N_{Ed}}{N_{cr}} \leq 0.04$ the buckling effect s may be ignored and only cross sectional checks apply.

(1) The non-dimensional slenderness

$$\bar{\lambda} = \sqrt{\frac{Af_y}{N_{cr}}} = \frac{L_{cr}}{i} = \frac{1}{\lambda_1} \text{ for class 1,2 or 3 cross-sections}$$

$$\bar{\lambda} = \sqrt{\frac{Af_y}{N_{cr}}} = \frac{L_{cr}}{i} \frac{\sqrt{\frac{A_{eff}}{A}}}{\lambda_1} \text{ for Class 4 cross-sections}$$

where L_{cr} is the buckling length in the buckling plane considered

i is the radius of gyration about the relevant axis, determined using the properties of the gross cross-section.

$$\lambda_1 = \pi \sqrt{\frac{E}{f_y}} = 93.9\varepsilon$$

$$\varepsilon = \sqrt{\frac{235}{f_y}} \quad (f_y \text{ in N/mm}^2)$$

α= is an imperfection factor that depends on

- Shape of the cross-section
- Direction of buckling (Y or Z axis)
- Fabrication process (hot-rolled, welded or cold-formed)

Table Imperfection Factors

Buckling Curve	*a*	*b*	*c*	*d*
Imperfection factor α	0.21	0.34	0.49	0.76

Values of the reduction factor χ can easily be obtained for the appropriate non-dimensional slenderness λ from Table 3.5

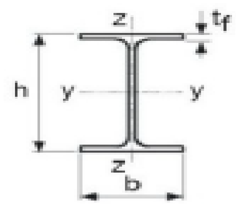
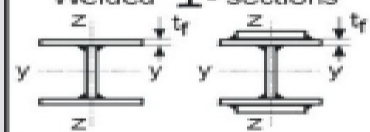
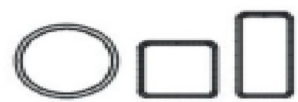
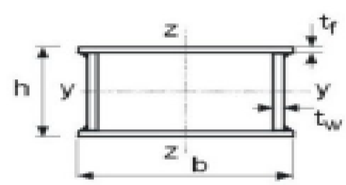
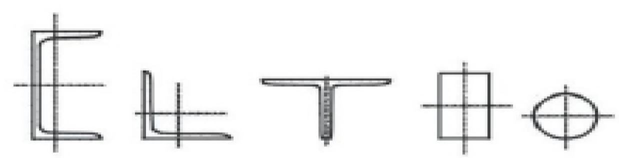
Table 3.5 Reduction factors χ

$\bar{\lambda}$	Reduction factor χ			
	Curve a	Curve b	Curve c	Curve d
0,2	1,0000	1,0000	1,0000	1,0000
0,3	0,9775	0,9641	0,9491	0,9235
0,4	0,9528	0,9261	0,8973	0,8504
0,5	0,9243	0,8842	0,8430	0,7793
0,6	0,8900	0,8371	0,7854	0,7100
0,7	0,8477	0,7837	0,7247	0,6431
0,8	0,7957	0,7245	0,6622	0,5797
0,9	0,7339	0,6612	0,5998	0,5208
1,0	0,6656	0,5970	0,5399	0,4671
1,1	0,5960	0,5352	0,4842	0,4189
1,2	0,5300	0,4781	0,4338	0,3762
1,3	0,4703	0,4269	0,3888	0,3385
1,4	0,4179	0,3817	0,3492	0,3055
1,5	0,3724	0,3422	0,3145	0,2766
1,6	0,3332	0,3079	0,2842	0,2512
1,7	0,2994	0,2781	0,2577	0,2289
1,8	0,2702	0,2521	0,2345	0,2093
1,9	0,2449	0,2294	0,2141	0,1920
2,0	0,2229	0,2095	0,1962	0,1766
2,1	0,2036	0,1920	0,1803	0,1630
2,2	0,1867	0,1765	0,1662	0,1508
2,3	0,1717	0,1628	0,1537	0,1399
2,4	0,1585	0,1506	0,1425	0,1302
2,5	0,1467	0,1397	0,1325	0,1214
2,6	0,1362	0,1299	0,1234	0,1134
2,7	0,1267	0,1211	0,1153	0,1062
2,8	0,1182	0,1132	0,1079	0,0997
2,9	0,1105	0,1060	0,1012	0,0937
3,0	0,1036	0,0994	0,0951	0,0882

For angles, they *y* and *z* axes should be taken as the *u* and *v* axes, respectively. For mono-symmetric sections, the *y* axis should be taken as the axis of symmetry. For point-symmetric

For flexural buckling, the approximate curve shall be determined from Table 3.4

Table 3.4 Selection of buckling curve for a cross section

Cross-section	Limits	Buckling about axis	Buckling curve
Rolled I - sections 	$h/b > 1,2$: $t_f \le 40$ mm	y - y z - z	a b
	$40\text{mm} < t_f \le 100$ mm	y - y z - z	b c
	$h/b \le 1,2$: $t_f \le 100$ mm	y - y z - z	b c
	$t_f > 100$ mm	y - y z - z	d d
Welded I - sections 	$t_f \le 40$ mm	y - y z - z	b c
	$t_f > 40$ mm	y - y z - z	c d
Hollow sections 	hot rolled	any	a
	cold formed - using f_{yb}	any	b
	cold formed - using f_{ya}	any	c
Welded box sections 	generally (except as below)	any	b
	thick welds and $b/t_f < 30$ $h/t_w < 30$	y - y z - z	c c
U-, L-, T- and solid sections 		any	c

<u>NOTE:</u>

F_{yb}; the bsic tensile yield strength of the basic metal out of which the member is made by cold-forming

F_{ya}: the average yield strength of a member after colding-forming and shall not exceed f_u or $1.2f_{yb}$.

$\beta = 1 - (y_0/r_0)^2$

Y_o = distance from shear center to centroid of gross cross-section along the y-axis.